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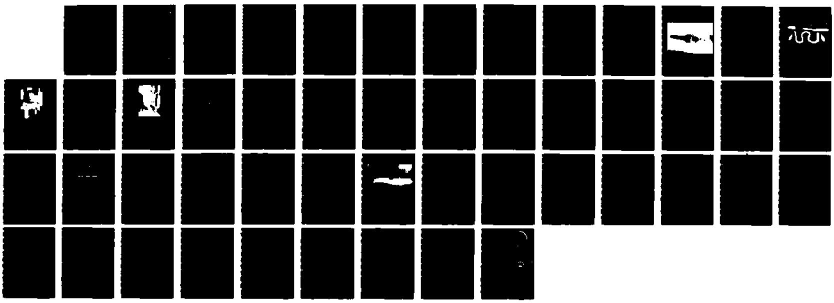

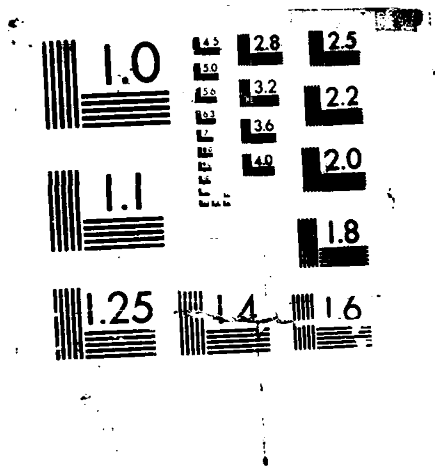

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Technical Report E06549-36
Contract No. N00039-84-C-0070

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RESPONSE OF THE WESTERN ELECTRIC MODEL 188A TEST SET (STOP LITE) TO ELF VOLTAGES

J. R. Gauger
R. M. Brosh

July 1987

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The Western Electric Model 188A Test Set (Stop Lite) is a hand-held probe that enables a telephone craftsman to detect hazardous voltages on metallic facilities without being endangered by electric shock. The facilities under test--metal pedestals, cable shields, cable suspension wires, and power line ground wires and rods--are ordinarily at the potential of the local earth. However, 60 Hz coupling from power lines, in combination with bad connections and/or grounding systems, can cause unexpected voltages to exist in common situations. The 188A test set is designed to detect 60 Hz ac voltages between 50 V and 20,000 V_{rms}.

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Item 19. Abstract (continued)

Extremely low frequency (ELF) voltages can also be induced on telephone cable shields and metallic equipment in areas where the telephone plant is collocated with an ELF communications system. This report addresses the question of how the 188A test set responds to such ELF voltages alone and to such voltages together with 60 Hz voltages. Laboratory mock-ups of typical telephone plant field installations were assembled, and tests were conducted to simulate various worst-case telephone fault conditions, such as a broken cable shield bond to ground. The report presents tabular and graphic data that document the response of the test set to a wide range of conditions. Variables considered include the effects of operating conditions such as user technique, ground cover, footwear, the response of the test set as a function of frequency, and its response to 60 Hz voltages together with modulated ELF voltages. Finally, the authors evaluate the effectiveness of the test set in detecting potentially hazardous ELF voltages.

FOREWORD

This report documents laboratory measurements made to determine the response of the Western Electric Model 188A Test Set (Stop Lite) to extremely low frequency (ELF) voltages on metallic equipment in a telephone plant. The test set is normally used by telephone craftsmen to detect the presence of hazardous 60 Hz voltages from power lines on equipment to be serviced. ELF voltages may also be present on such equipment in areas near an ELF communications system.

This work was funded by the Space and Naval Warfare Systems Command, Communications Systems Project Office, under Contract N00039-84-C-0070, to IIT Research Institute (IITRI). These tests were performed by J. R. Gauger and R. M. Brosh.

Respectfully submitted,
IIT RESEARCH INSTITUTE

J. R. Gauger
Senior Engineer

R. M. Brosh
Assistant Engineer

Approved

R. D. Carlson
Program Manager

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FIGURES AND TABLES

FIGURES AND TABLES (continued)

RESPONSE OF THE WESTERN ELECTRIC MODEL 188A TEST SET (STOP LITE) TO ELF VOLTAGES

1. INTRODUCTION

The Western Electric Model 188A Test Set (Stop Lite) is a hand-held probe that enables a telephone craftsman to detect hazardous voltages on metallic facilities without being endangered by electric shock (see Figure 1). The facilities under test--metal pedestals, cable shields, cable suspension wires, and power line ground wires and rods--are ordinarily at the potential of the local earth. However, 60 Hz coupling from power lines, in combination with bad connections and/or grounding systems, can cause unexpected voltages to exist in common situations. The 188A test set is designed to detect 60 Hz ac voltages between 50 V and 20,000 V_{rms}. The 50 V threshold reflects the maximum safe working voltage for a craftsman; the 20,000 V limit is the maximum voltage a craftsman might encounter on power distribution systems in shared rights-of-way.

Extremely low frequency (ELF) voltages can also be induced on telephone cable shields and metallic equipment in areas where the telephone plant is collocated with an ELF communications system. This report addresses the question of how the 188A test set responds to such ELF voltages alone and to such voltages together with 60 Hz voltages. Laboratory mock-ups of typical telephone plant field installations were assembled, and tests were conducted to simulate various worst-case telephone fault conditions, such as a broken cable shield bond to ground. The report presents tabular and graphic data that document the response of the test set to a wide range of conditions. Variables considered include the effects of operating conditions such as user technique, ground cover, footwear, the response of the test set as a function of frequency, and its response to 60 Hz voltages together with modulated ELF voltages. Finally, the authors evaluate the effectiveness of the test set in detecting potentially hazardous ELF voltages.

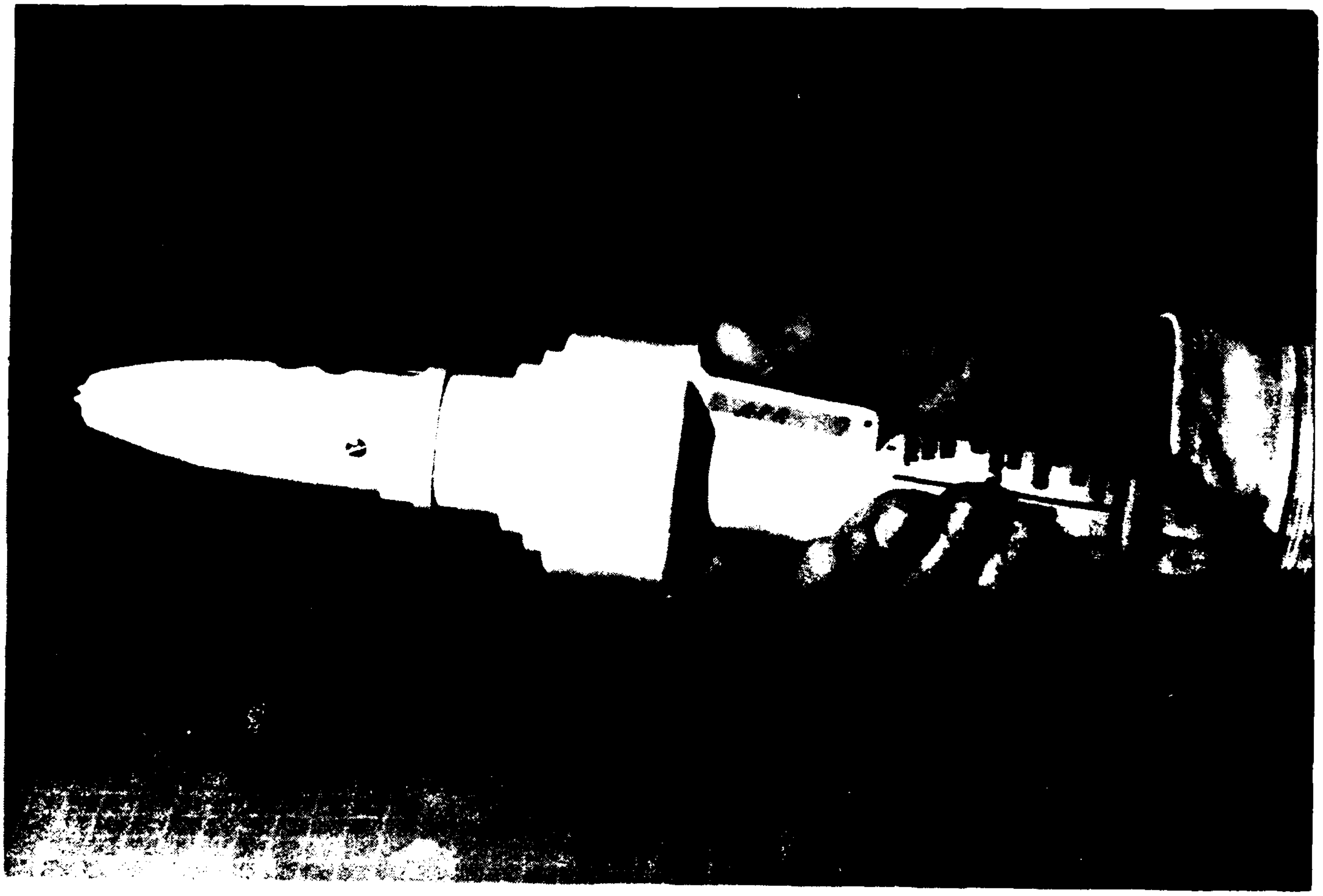

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FIGURE 1. PHOTOGRAPH OF WE 188A TEST SET.

2. TEST SET OPERATION

2.1 Test Set Description

The 188A test set consists of the main probe body, a conductive cap, and a retractile (W1BU) cord, as shown in Figure 2.

The body of the 188A test set is a yellow plastic cylinder that weighs approximately 1 lb. Its front housing includes a carbide probe tip, red and green light-emitting diodes (LEDs), a ground post (not shown), and a battery check contact. The front section is separated from the handle by a flash guard. The handle contains an operating switch and a belt clip.

The black conductive cap fits either over the front section, as a protector for the probe tip during storage, or over the end of the handle when used with the W1BU cord to provide a ground reference. The W1BU cord is a black retractile single conductor equipped with an insulated alligator clip at each end.

2.2 Operation Procedure

Before the craftsman comes in contact with the object to be tested, he performs a checkout procedure on the 188A test set to be sure that it is in working order. He then proceeds with the safety test as follows: The test set is grasped as shown in Figure 1, and the switch is pushed down and held so that the green LED lights up; the probe tip is placed in electrical contact with the object under test as shown in Figure 3. A steady green light tells the craftsman the object is safe to touch. A flashing red light signifies a hazardous voltage; in such a case, the craftsman must not work on the object until necessary precautions are taken.[1]

There are two situations in which the W1BU cord is used while performing a safety test:

(1) When the craftsman does not have his feet on the ground, such as when climbing a pole (no ground reference).

(2) When the craftsman supposes that there may be electrostatic coupling, such as near a high voltage line (capacitive coupling from external electric field to user causes secondary induced voltage).

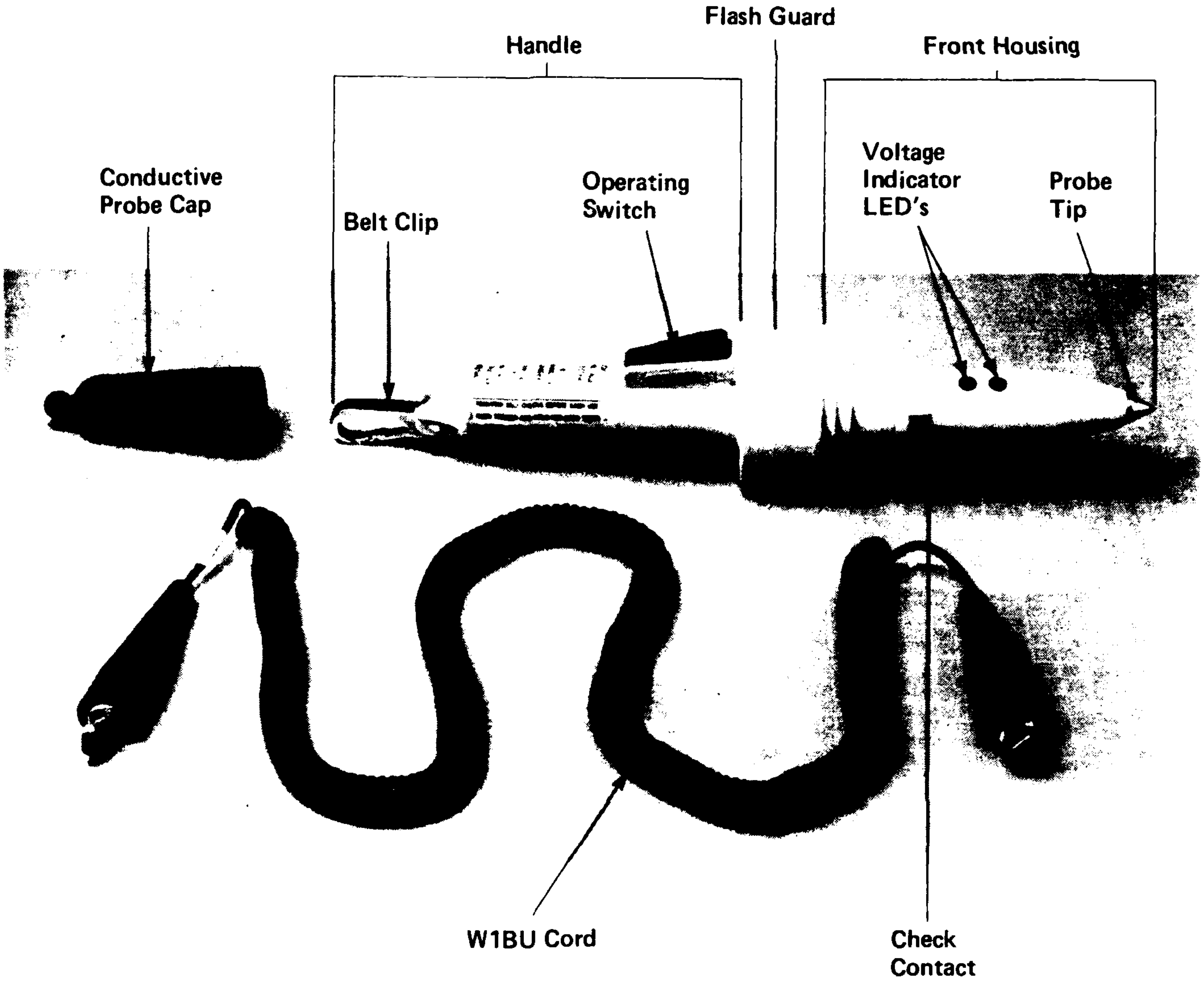

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FIGURE 2. COMPONENT PARTS OF WE188A TEST SET.

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FIGURE 3. MEASUREMENT.

In either case, the conductive cap is placed on the handle of the 188A test set. One end of the W1BU cord is clipped to the conductive cap, and the other end is connected to a known ground such as a ground rod. The safety test is performed as previously described. Figure 4 shows a measurement using the conductive cap and the W1BU cord.

2.3 Theory of Probe Operation

The 188A test set is essentially a high input impedance, battery-powered voltage detector. When hand-held, the test set's input impedance is placed in series with the user's impedance to ground, forming a voltage divider with the user himself acting as the lower leg of the divider. Figure 5 shows an equivalent circuit of the test set under normal test conditions. A voltage applied to the probe tip, V_S, causes a very small current to flow through the voltage divider, and thus through the body of the user. The test set senses the resultant voltage drop, V_P, across the probe resistance, R_P. The voltage, V_P, across the resistor is dependent on the total impedance, Z_T, to ground:

$$V_P = V_S\left(\frac{R_P}{R_P + Z_T}\right)$$

The test set input impedance, R_P, is essentially resistive and constant in value. The test set's voltage detector is triggered when the voltage across R_P is approximately 4 V (experimentally determined). The value of Z_T, however, is highly variable and dependent on several factors including the capacitance between the test set and the user, the impedance (resistance) of the user's body, and the capacitance of the user's body to ground as a function of footwear and local ground cover.

The total impedance, Z_T, can be subdivided into three elements in series as shown in Figure 6: Capacitance C_{PH}, the capacitance from the inner metal tube of the 188A test set handle to the hand of the user; resistance R_B, the resistance of the body of the user; and capacitance C_{BG}, the capacitance from the body of the user to ground. The body resistance, R_B, usually a few thousand ohms, is small in comparison with the capacitive reactances of C_{PH} and C_{BG}, and can be ignored. C_{PH}, the capacitance of the inner metal tube of the test set handle to the hand of the user, is dependent on the surface area of the hand and is a function of hand size, perspiration, and pressure and

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FIGURE 4. MEASUREMENT USING CONDUCTIVE CAP AND W1BU CORD AS A GROUND REFERENCE.

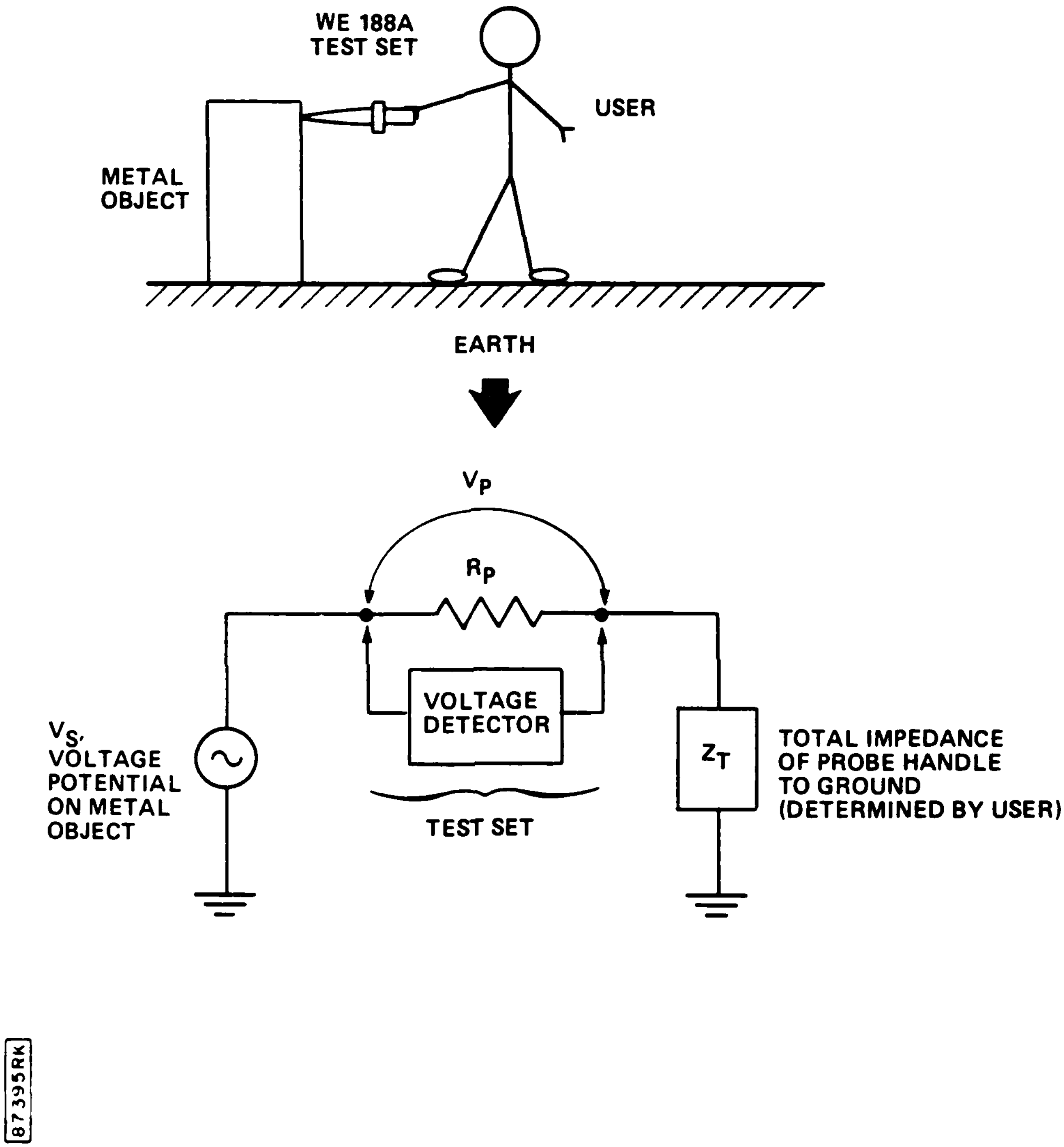


FIGURE 5. EQUIVALENT CIRCUIT OF WE 188A TEST SET, USER, AND DEVICE-UNDER-TEST.

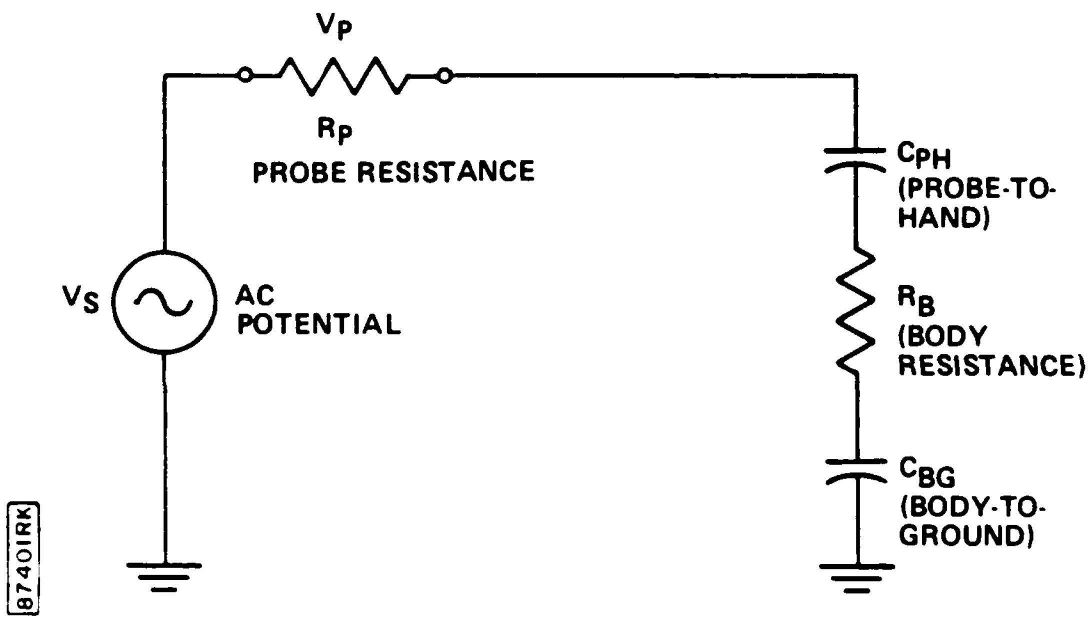


FIGURE 6. EQUIVALENT CIRCUIT OF WE 188A TEST SET.

location of grasp. C_{BG}, the capacitance of the user's body to ground, is dependent on body and foot size, thickness and composition of the footwear sole, and thickness and composition of the local ground cover.

These series capacitances combine so that the total series capacitance, C_T, is less than the smallest individual capacitance:

$$C_T = \frac{1}{1/C_{PH} + 1/C_{BG}}$$

Thus, impedance Z_T is primarily capacitive, and its value is a direct function of frequency. As a result, the level of voltage of a device-under-test that will trigger the tests set's warning LED will be a function of both the frequency of the voltage and the characteristics of the user.

The 188A test set functions in a similar manner when used with the conductive cap, W1BU cord, and a local ground rod. The cord and cap provide an additional impedance from the test set handle to ground which is in parallel with that provided by the user. This impedance consists of the capacitance from the test set handle to the conductive cap, C_{PC}, in series with the resistance of the cap itself, R_C, as illustrated in Figure 7. If the user's hand makes direct contact with the conductive cap, C_{PC} and C_{PH} are essentially placed in parallel, as shown by the dashed line. The effect on the test set's response of the added shunt impedance provided by the cap and cord is a function of the measurement scenario. On the ground, the shunt impedance tends to stabilize variations in the user's capacitance to ground and manner of using the test set, increases the test set's sensitivity, and negates the influence of external capacitive coupling to the user. When the user is positioned above ground level, such as on a utility pole, the user's capacitance to ground is very small. The cap and cord then provide a sufficiently low impedance to ground to maintain the minimum sensitivity requirement of the test set.

3. TEST SETUP AND EQUIPMENT

3.1 Typical Telephone Plant Configurations

This section describes typical telepone plant configurations that a craftsman might encounter in an area where the telephone plant is collocated with an ELF communications system. In ELF system areas, interference

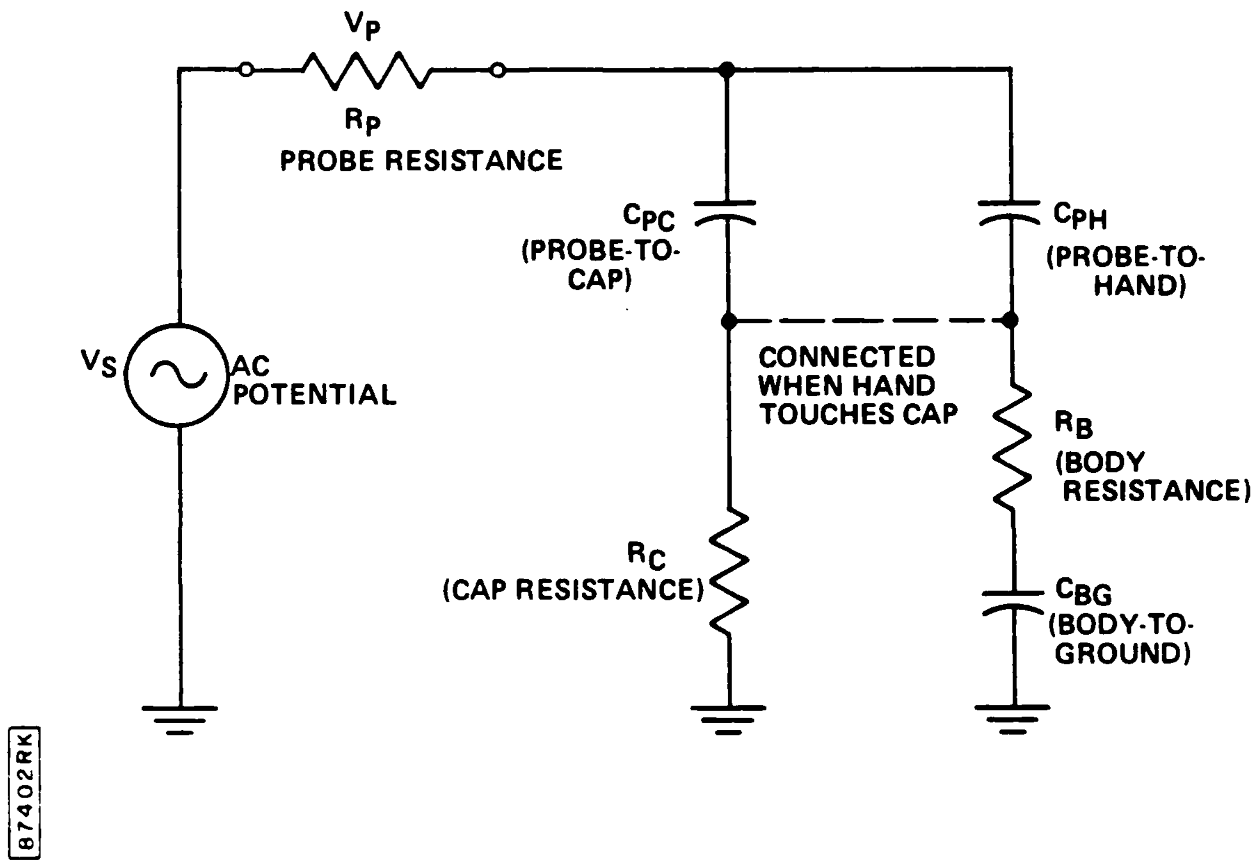


FIGURE 7. EQUIVALENT CIRCUIT OF WE 188A TEST SET USING CONDUCTIVE CAP AND W1BU CORD.

mitigation protocol calls for a maximum allowable voltage of 50 V on any telephone plant conductor and for voltages on appurtenances accessible to the public, such as telephone pedestal cases, to be limited for public safety considerations to a maximum of 6 V with respect to remote earth. This protocol is reflected in the five configurations described below.

3.1.1 Configuration 1: $V_{SG} \leq 6$ V

Figure 8 depicts a normal metal pedestal configuration. This configuration is employed in portions of the plant where ELF induced shield-to-remote ground voltages (V_{SG}) are under 6 V. The shields are connected to the pedestal, which in turn is connected to earth ground by a metal stake. The metal stake may or may not be painted; in any case, it is generally a poor connection to ground.

3.1.2 Configuration 2: $6 \text{ V} < V_{SG} \leq 50$ V

Where unmitigated shield-to-remote-ground voltages exceed 6 V, but are less than 50 V, Configuration 2 is used to ensure safety (see Figure 9). Here public exposure is limited by isolating the cable shields from an existing metal pedestal or by installing a nonconductive pedestal. The cable shields are tied to each other and to a buried ground rod via an insulated wire. The ground rod is spaced at least 10 ft from a metal pedestal.

3.1.3 Configuration 3: $V_{SG} > 50$ V

Figure 10 represents the pedestal configuration that is used together with other plant treatments to ensure public and craftsman safety in areas where ELF induced voltages would otherwise be greater than 50 V. The pedestal may be either metal or fiberglass. The shields are isolated from each other and from the pedestal, and are connected via insulated wire to separate buried ground rods spaced at least 10 ft from the pedestal. A spark gap may be incorporated to provide additional lightning protection.

3.1.4 Configuration 4: $6 \text{ V} < V_{SG} \leq 50$ V, Metal Case

Configuration 4 will be used where isolation is needed for public safety assurance, but where large metal-cased equipment is already in place and shield isolation or the use of a nonconductive closure is undesirable. As shown in Figure 11, a buried "ground ring" (generally a wire rectangle

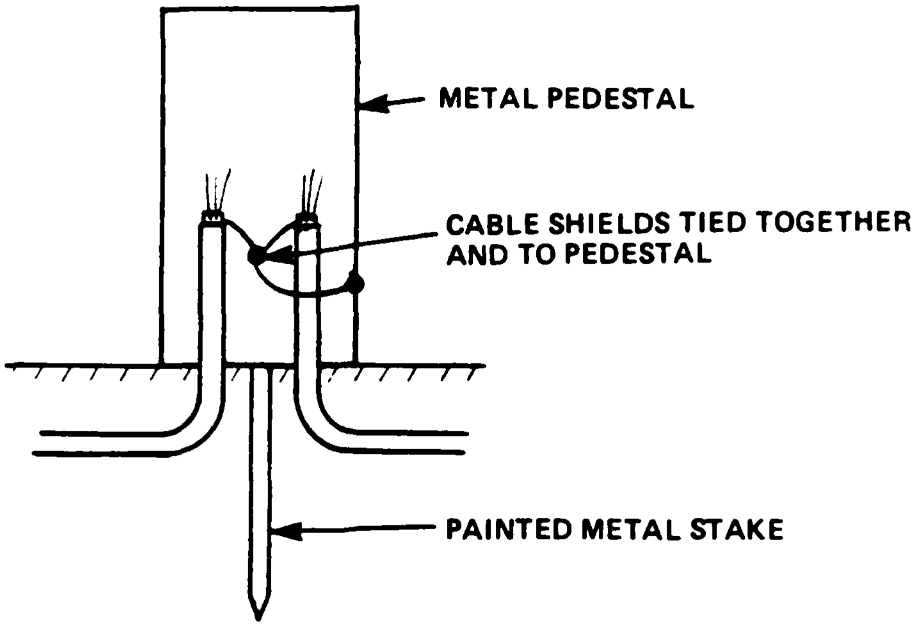


FIGURE 8. CONFIGURATION 1: METAL PEDESTAL, $V_{SG} \leq 6$ V.

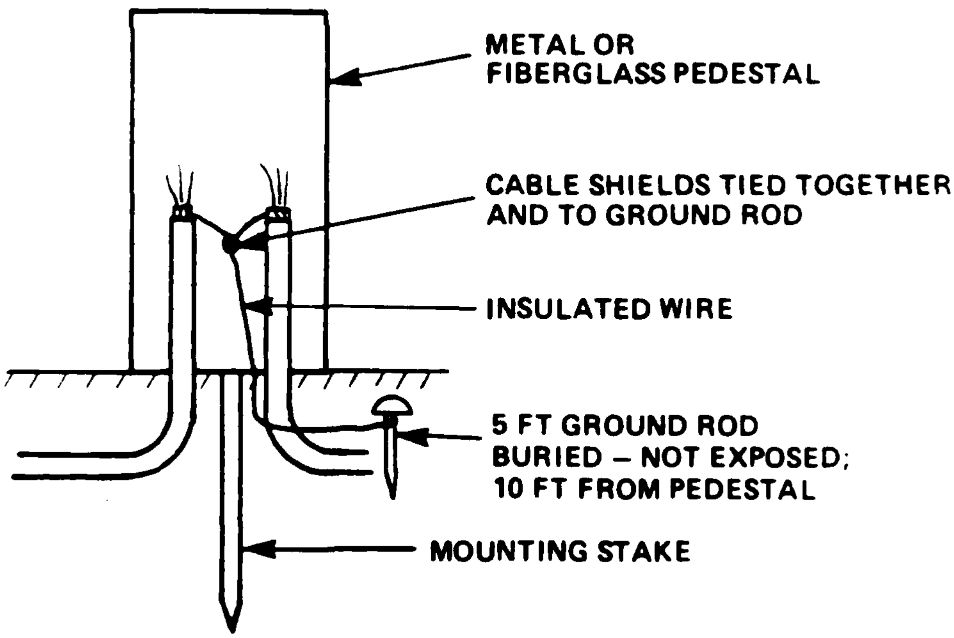


FIGURE 9. CONFIGURATION 2: METAL OR FIBERGLASS PEDESTAL, $6 \text{ V} < V_{SG} \leq 50$ V.

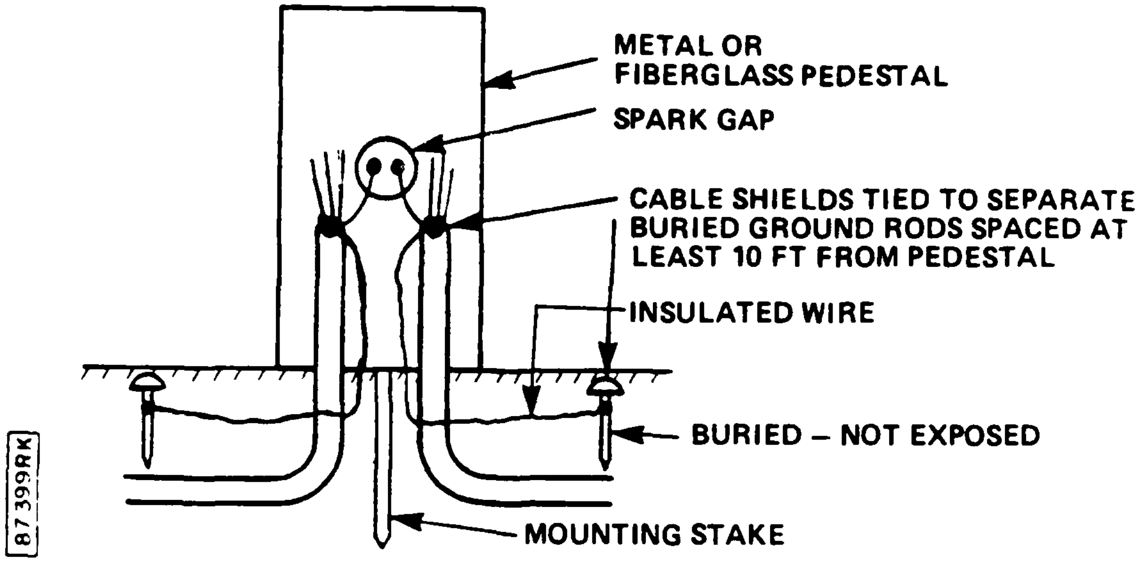
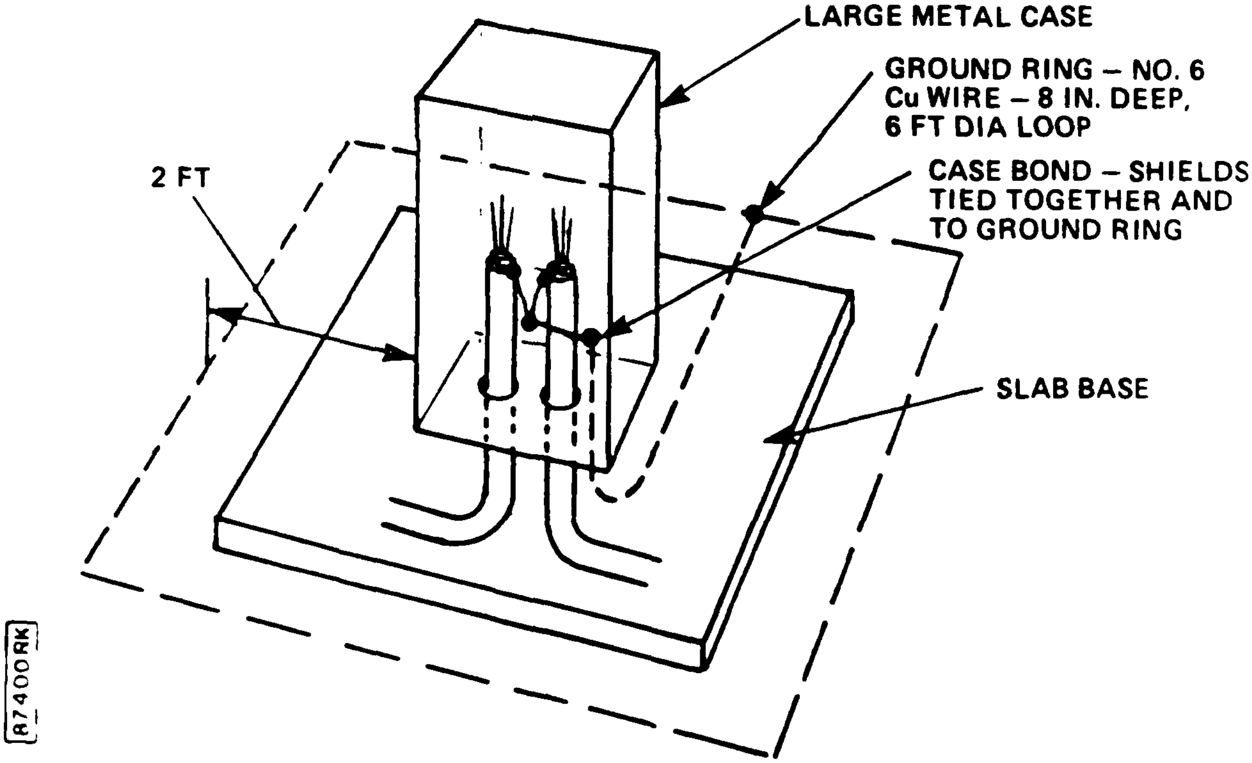


FIGURE 10. CONFIGURATION 3: METAL OR FIBERGLASS PEDESTAL, $V_{SG} > 50V$.



SHIELDS CONNECTED TOGETHER AND TO CASE AND ALSO TO GUARD/GROUND RING TO RAISE LOCAL TOUCH POTENTIAL

FIGURE 11. CONFIGURATION 4: LARGE METAL PEDESTAL CONNECTED TO A GROUND RING, $6 < V_{SG} \leq 50V$.

approximately 6 ft square) is installed around the metal case. The cable shields are tied to the metal case and to the ground ring. This has the effect of raising the local ground potential above and inside the ring so that the touch potential between the metal case and local ground is less than 6 V. This technique is employed by telephone companies to mitigate 60 Hz induction.[2]

3.1.5 Configuration 5: Aerial Telephone Cable

Configuration 5, shown in Figure 12, represents an aerial telephone cable where the shield of the telephone cable is bonded to the multigrounded neutral wire of a collocated power distribution system. In this situation, the craftsman would use the conductive cap of the test set, the W1BU cord, and a separate ground rod to provide the proper ground impedance for the test set.

3.2 Laboratory Simulation of the Telephone Plant

Laboratory mock-ups of the telephone plant configurations described above were constructed to allow simulation of ELF-induced shield and equipment voltages under controlled and uniform conditions. Voltages were applied to the test setups in such a manner as to replicate worst-case field conditions for hazard voltages such as bad grounds, broken shield bonds, and floating (ungrounded) shields.

For configurations 1 through 3, the laboratory mock-ups were constructed by laying out a 12-ft-square ground mat, using paper-backed copper foil to simulate the local earth's surface. Worst-case insulating ground cover was simulated with a layer of high-density styrofoam sheet, 1 in. thick and 8 ft square, placed on top of the foil. The foam was removable. In this manner the effect of ground cover on the response of the test set could be bounded for laboratory testing. The best or most sensitive case would be with the foam removed, simulating bare earth. The worst or least sensitive case would be with the foam in place, simulating a dry concrete pedestal or equipment mounting pad, crushed stone, or thick underbrush. The "pedestals" were aluminum or fiberglass boxes mounted on a wooden stand placed in the center of the styrofoam sheet. Two lengths of shielded, multi-pair telephone cable were run from opposite sides of the ground mat into the simulated pedestals.

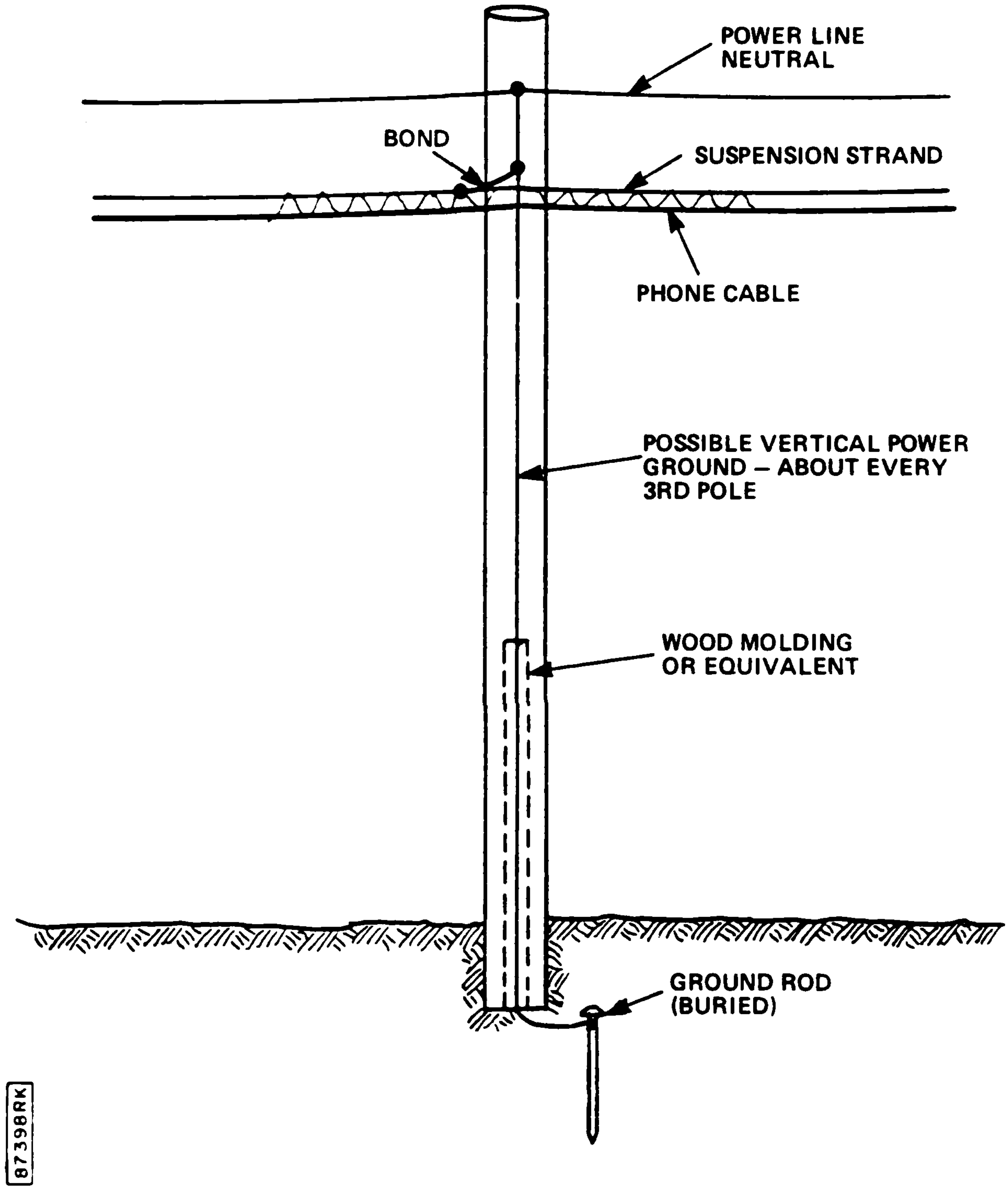


FIGURE 12. CONFIGURATION 5: AERIAL TELEPHONE CABLE.

For the mock-up of configuration 4, a second layer of copper foil 6-ft square was placed on top of the styrofoam sheet to simulate the effect of a ground ring, and a second removable layer of styrofoam was overlaid on this ground ring mat to simulate ground cover.

The laboratory mock-up for the aerial phone cable of configuration 5 was done in a high-bay area with a 25-ft ceiling. A 10-ft wooden stepladder was placed on a copper foil ground mat to provide an elevated, nonconductive work station, to simulate the conditions encountered by a craftsman on a pole. A fiberglass pole with a metal box at one end was lashed to the back of the ladder to provide a metallic contact at a height of about 14 ft. The box was energized by a test lead running horizontally from a wall about 15 ft from the ladder.

The layouts of the laboratory mock-ups are illustrated in Figures 13 through 16. These figures also show the wiring connections between the cable shields, "pedestals," shield drive voltage sources, and ground mat(s).

The mock-up for pedestal configurations 1 and 2 (Figure 13) shows the two cable shields A and B connected to each other and to the pedestal for configuration 1, and driven by a voltage source referenced to the ground mat. This connection simulates an open shield ground (configuration 2) or open pedestal ground (configuration 1).

Wiring connections for pedestal configuration 3 are shown in Figure 14. Here cable shields A and B are shown as isolated from each other and from the pedestal, simulating a gapped shield situation. Each shield is driven by an independent voltage source referenced to the ground mat to simulate the effect of open shield grounds. The voltage sources may be driven 180 degrees out of phase with each other as a worst-case shield voltage scenario.

The wiring connections for the mock-up of pedestal configuration 4 are more complex due to the extra ground mat used to simulate the buried ground ring (Figure 15). For this setup, the shield of cable A is bonded to the metal pedestal and to the ground ring mat, a normal field condition. A voltage source is connected between shield A and the ground mat, simulating the elevated potential of the ground ring with respect to remote ground. In addition, a second voltage source is connected between shield A and shield B.

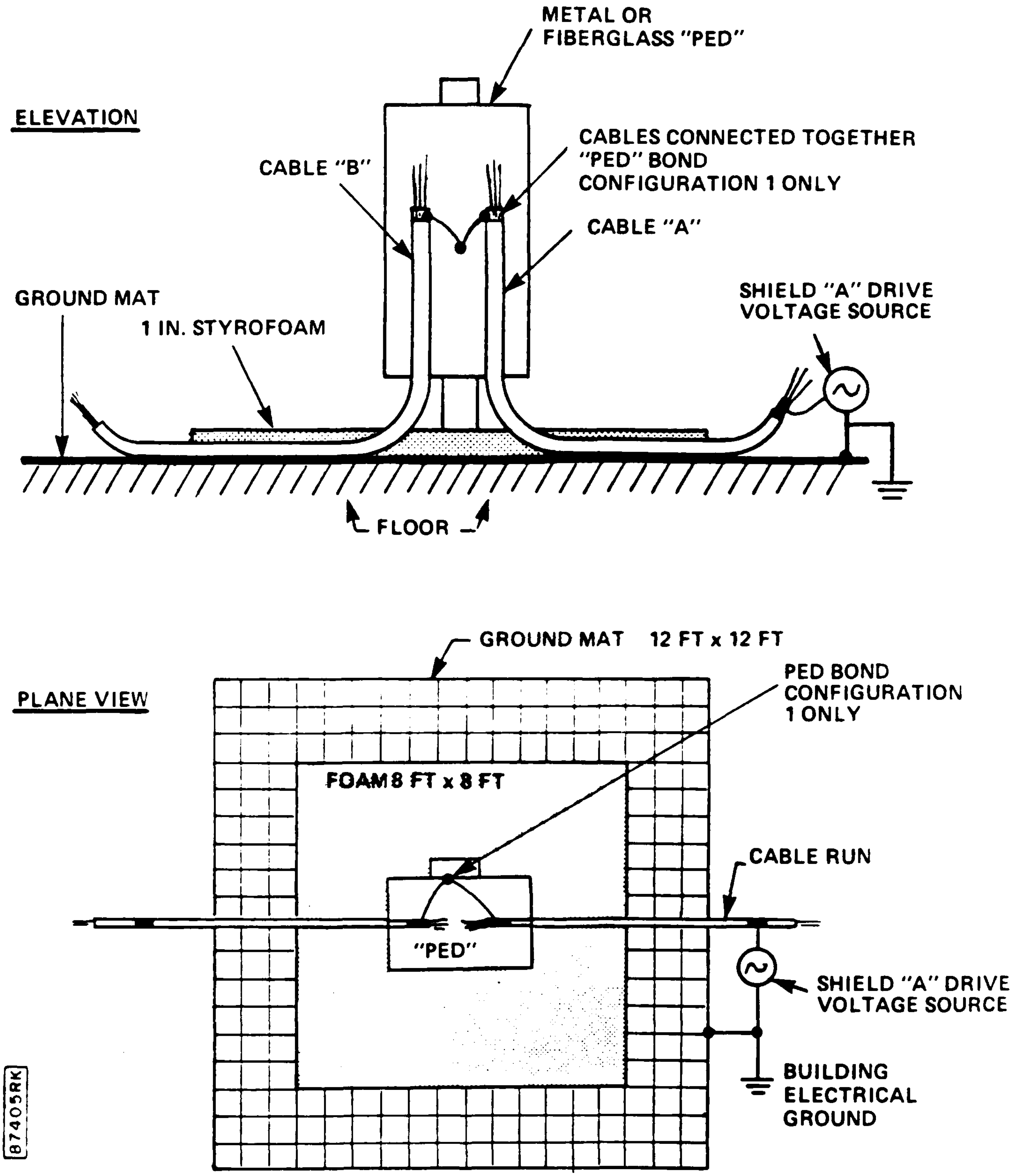


FIGURE 13. LABORATORY MOCK-UP FOR PEDESTAL CONFIGURATIONS 1 AND 2 WITH SIMULATED OPEN SHIELD OR PEDESTAL GROUND.

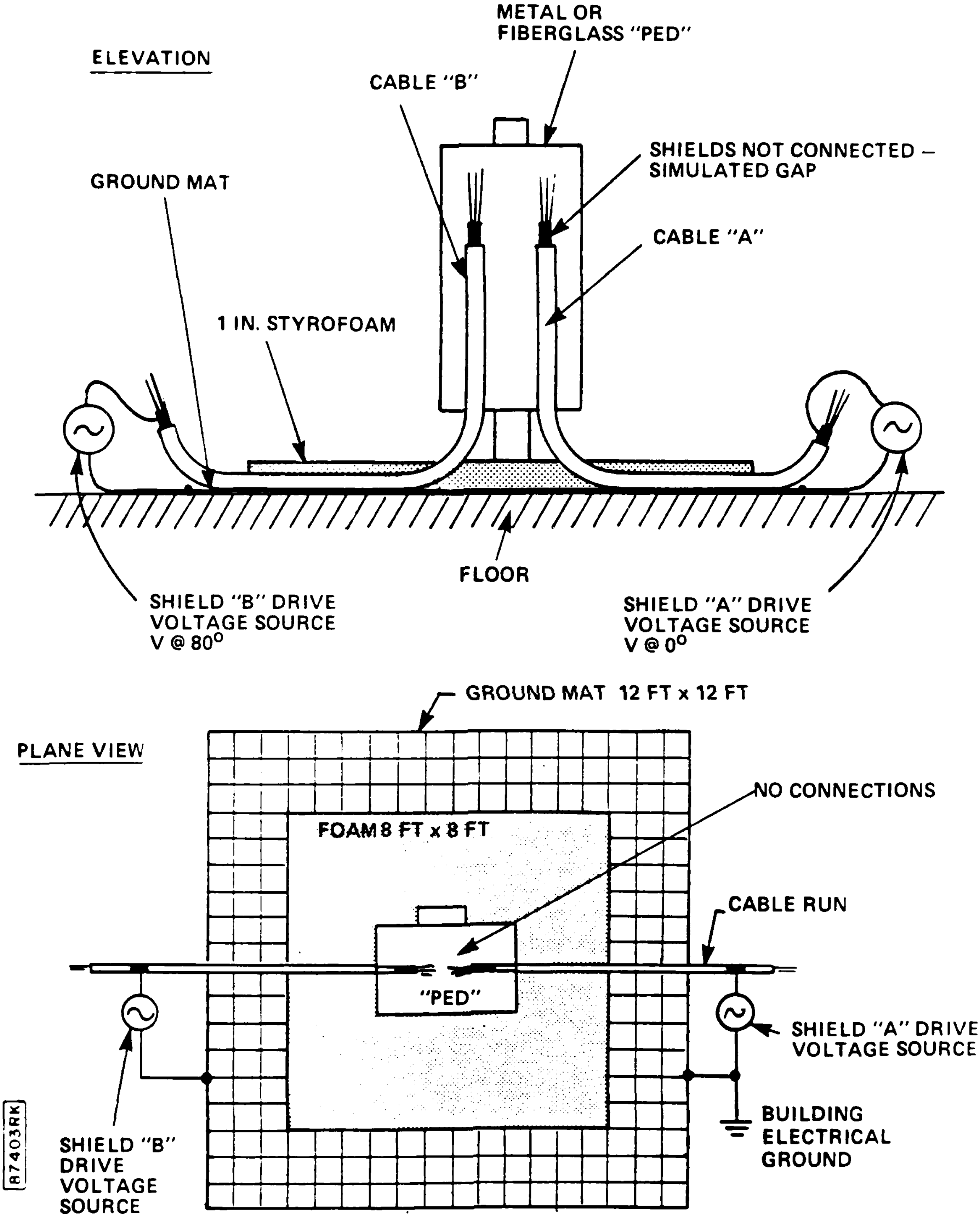


FIGURE 14. LABORATORY MOCK-UP FOR PEDESTAL CONFIGURATION 3 WITH SIMULATED GAPPED SHIELDS AND OPEN SHIELD GROUNDS.

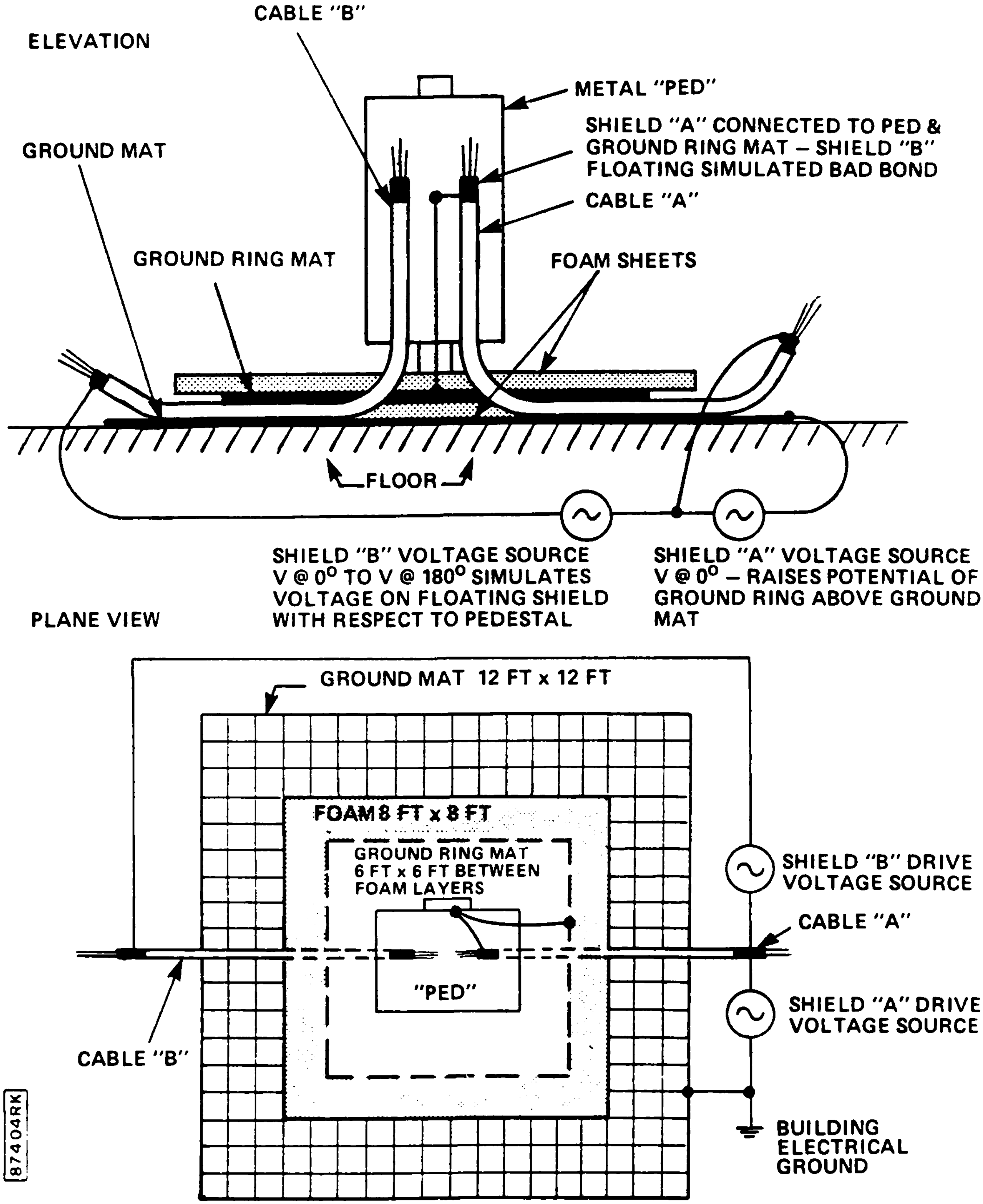


FIGURE 15. LABORATORY MOCK-UP FOR PEDESTAL CONFIGURATION 4 WITH SIMULATED BROKEN SHIELD BOND.

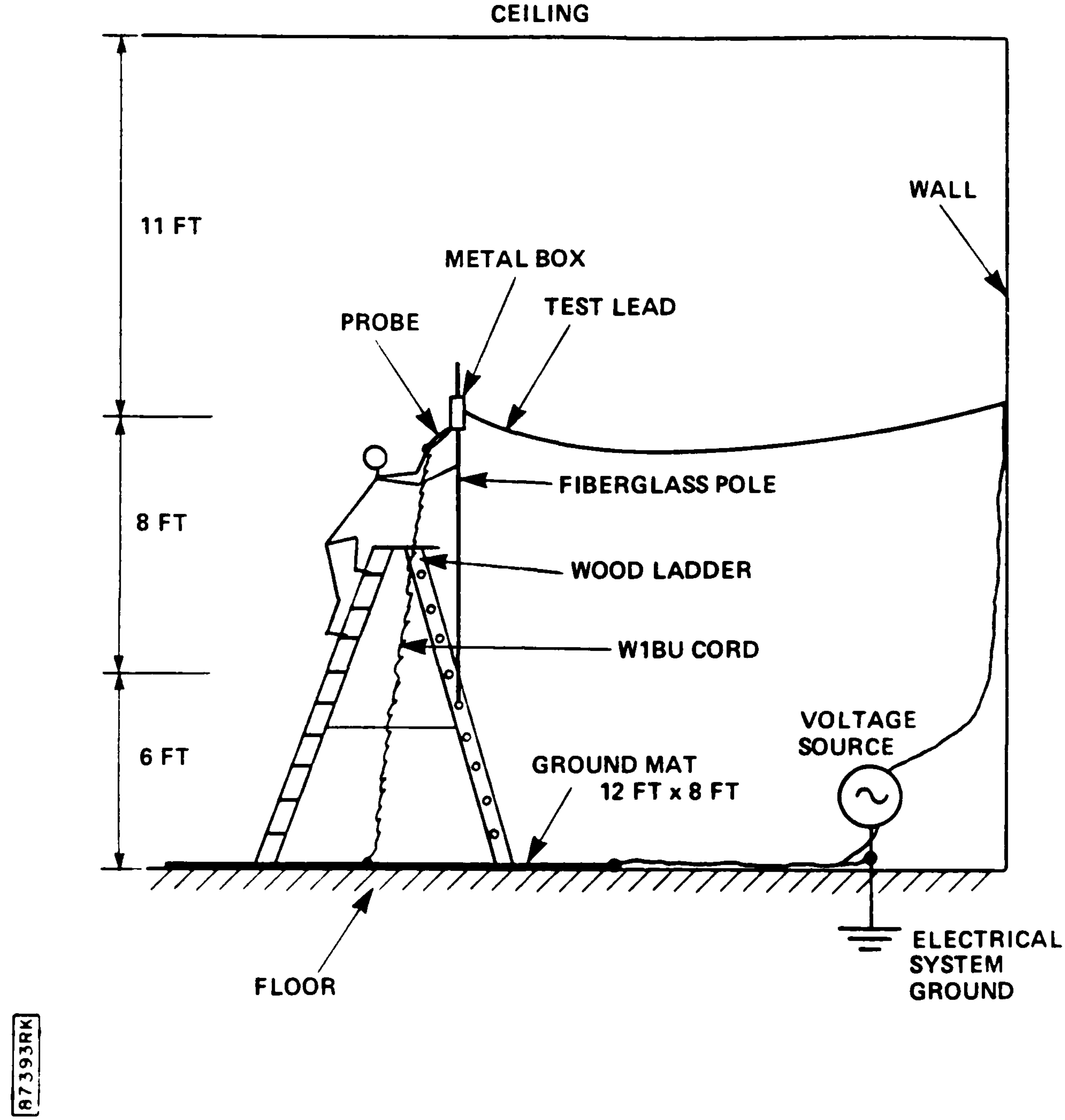


FIGURE 16. LABORATORY MOCK-UP FOR CONFIGURATION 5 – VOLTAGE ON AERIAL PHONE CABLE WITH RESPECT TO LOCAL GROUND.

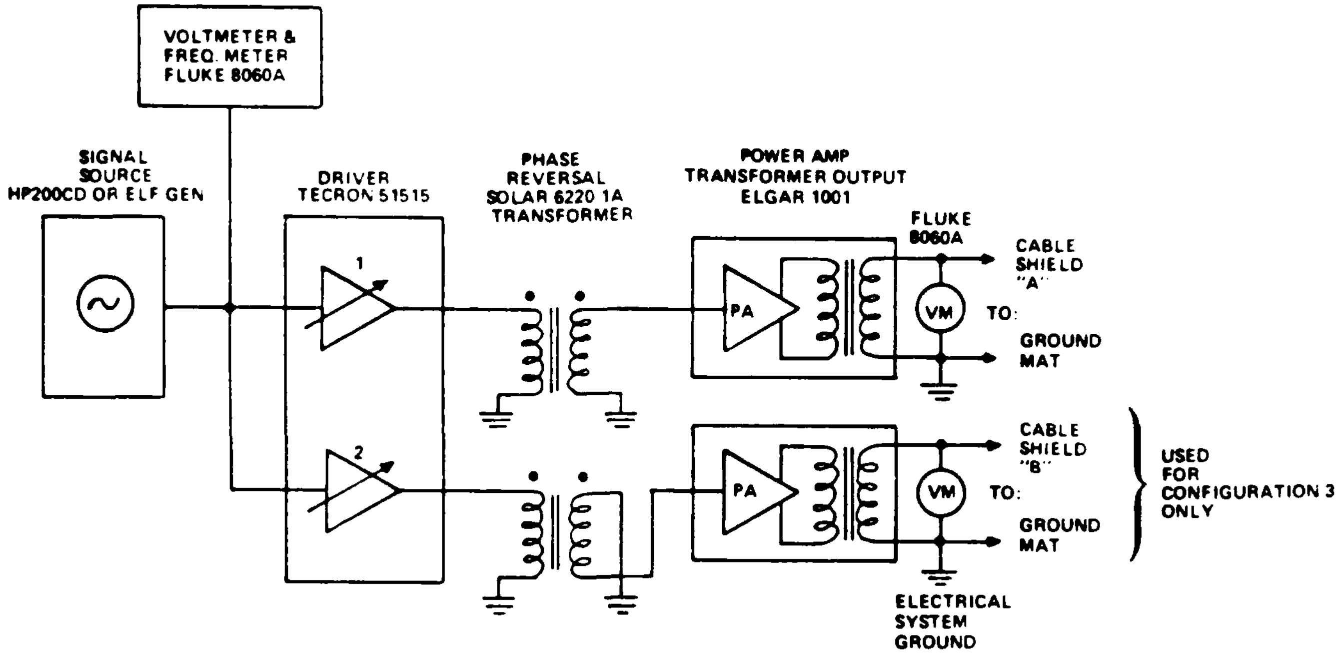
This source can be either in phase or 180 degrees out of phase with the first source, and simulates an open pedestal bond on shield B.

The wiring connections for the aerial cable mock-up are shown in Figure 16. The metal box that simulates an aerial cable shield or suspension wire is driven by a test lead connected to the high side of the voltage source. The ground mat is connected to the low side of the source, and may be connected to the electrical system ground at the voltage source. This setup simulates a voltage on an aerial cable with respect to local earth ground.

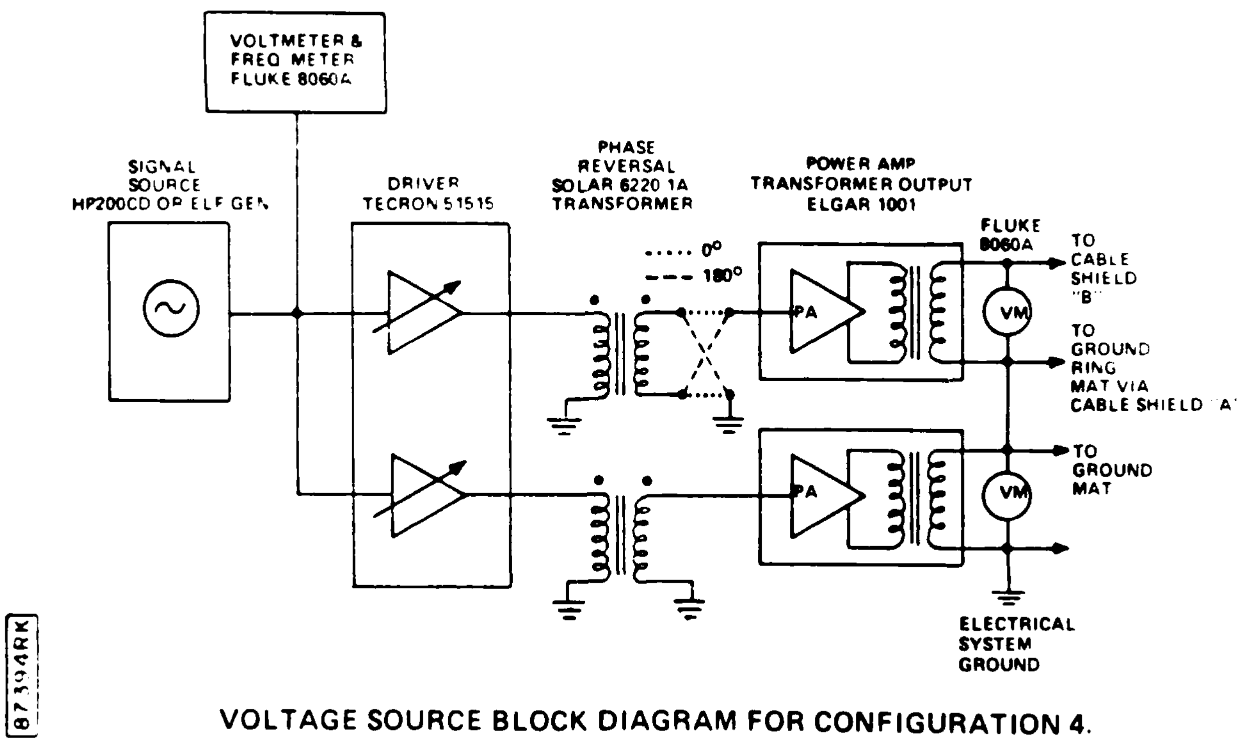
The shield drive voltage sources shown in Figures 13 through 16 were generated according to the block diagrams of Figure 17. A Hewlett-Packard 200CD audio oscillator and an IITRI MSK Generator were used to generate low-level CW (single frequency) and modulated ELF voltages, respectively. A Tecron 5515 dual-channel amplifier served as a variable gain driver for a pair of Solar audio-isolation transformers. The transformers allowed phase reversal between channels. Key to implementing the voltage sources were a pair of Elgar power amplifiers with transformer-coupled outputs. These outputs were not ground referenced, but could be floated so as to place two voltage sources in series as required for the mock-up of configuration 4. Fluke 8060A true rms digital multimeters were used to monitor all voltages.

3.3 Controlling Probe-to-Ground Capacitance

A series of preliminary tests were conducted prior to performing complete test set response characterizations in order to assess the relationship of test set response to user-dependent parameters. Initially, concern focused on the effects of footwear composition and ground cover. These factors were shown to have a significant impact on test set response, as expected. However, for a particular type of footwear or thickness of ground insulating material, test set response was found to be fairly consistent and repeatable over time. This was not the case for variations caused by changes in the user's grip on or contact with the handle of the test set. Seemingly insignificant changes in hand grip location, pressure, area, or sweatiness of the palm caused variations on the same order as those caused by changes in frequency or ground cover, thus precluding repeatable response data. This problem was overcome by controlling the area of effective hand grip via the application of a measured area of copper foil to the test set handle. The



VOLTAGE SOURCE BLOCK DIAGRAM FOR CONFIGURATIONS 1, 2, 3, AND 5.



VOLTAGE SOURCE BLOCK DIAGRAM FOR CONFIGURATION 4.

FIGURE 17. SHIELD DRIVE VOLTAGE SOURCES FOR LABORATORY TELEPHONE PEDESTAL MOCK-UPS.

foil area needed was determined empirically by matching test set response using the foil to the average response obtained with hand grip only. Figure 18 shows the test set with the foil area applied.

The preliminary experiments also allowed the measurement or calculation of approximate values for the probe-to-ground impedance elements identified in Figure 7. A summary of the element values is presented in Table 1. Of particular interest are the values for the probe-to-hand capacitance C_{PH} and the body-to-ground capacitance C_{BG}. The value of C_{PH} is that obtained for a 150-lb male with average hand size. It is also the value of the probe-to-foil capacitance measured with the foil covering on the handle. The values for C_{BG} show the effects of footwear and ground cover, which control the distance between the user's feet and bare earth. As the values of capacitors in series combine according to the formula $1/C_T = 1/C_{BG} + 1/C_{PH}$ the value of the probe capacitance to ground, C_T, will always be less than the smallest series capacitance. The probe impedance to ground, Z_T, which determines its sensitivity, is inversely related to C_T and frequency, f, as follows:

$$Z_T = \frac{1}{2\pi f C_T}$$

Thus, the sensitivity of the WE 188A test set increases with frequency and as the user coupling (capacitance) to ground increases. Maximum coupling occurs when the user is barefoot, standing on bare earth, and holding the test set bare-handed with both hands so as to completely cover the handle. Similarly, probe sensitivity decreases with decreasing frequency, and with decreased probe-to-ground coupling (i.e., thick footwear, thick ground cover, small hand grip area).

The WE 188A test set response characterizations discussed in Section 4 were conducted using typical best-case and worst-case sensitivity test conditions as determined by the test set's coupling to ground.

4. WE 188A RESPONSE TEST RESULTS

The tests documented in this section were performed with the WE 188A test set used by an adult male of average height and weight (5 ft, 9 in.; 150 lb). The same individual performed all tests.

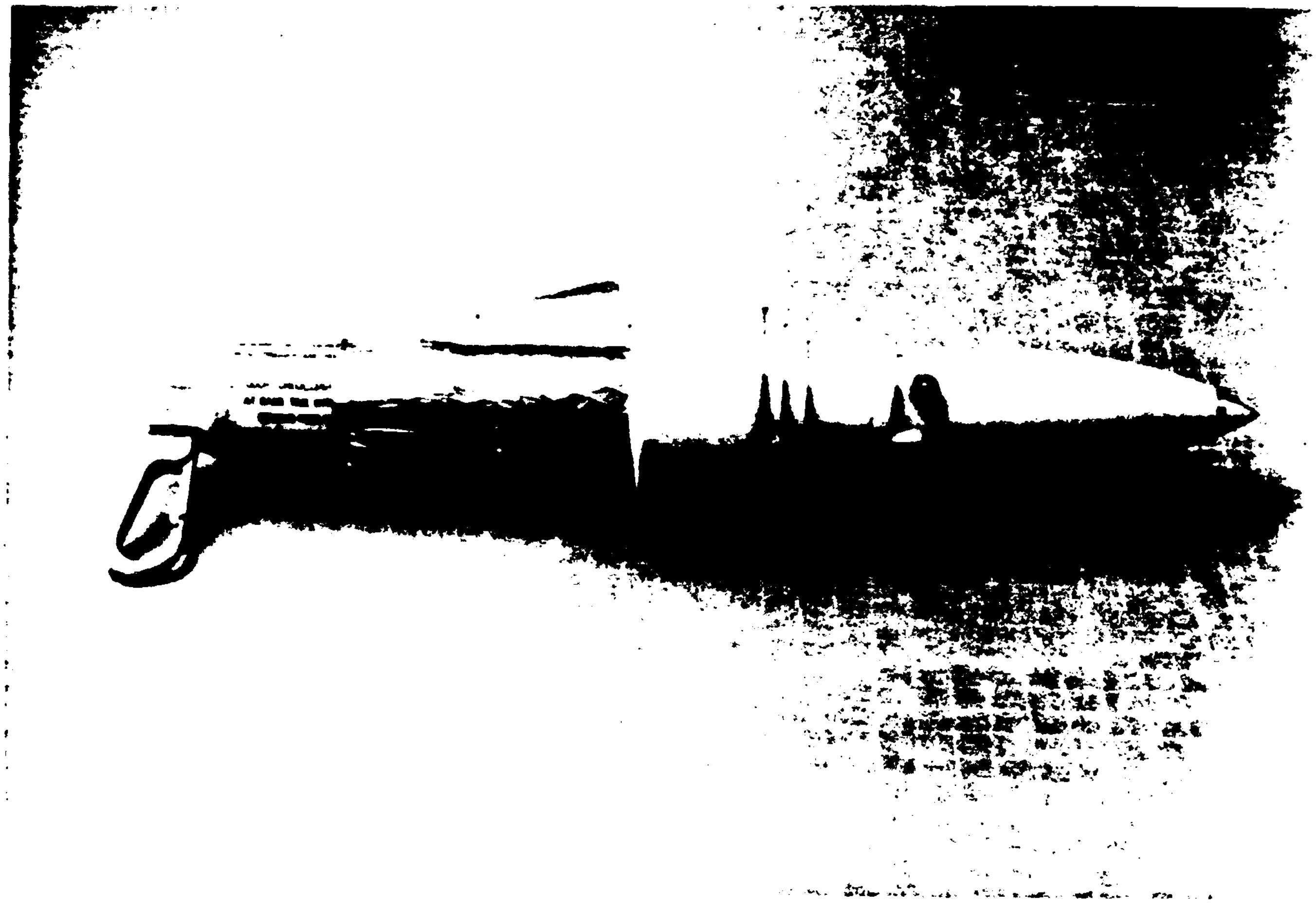


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FIGURE 18. WE 188A TEST SET WITH FOIL APPLIED TO HANDLE TO CONTROL EFFECTIVE HAND GRIP AREA.

TABLE 1. PROBE-TO-GROUND IMPEDANCE VALUES

Impedance Element	Approximate Element Value	Description/Condition
R_P	10 MΩ	Probe resistance (measured)
R_B	1-10 kΩ	Body resistance (estimated)
R_C	60 MΩ	Conductive cap resistance (calculated)
C_{PH}	44 pF	Probe-to-hand capacitance (calculated)
C_{PC}	26 pF	Probe-to-cap capacitance (calculated)
C_{BG}		Body-to-ground capacitance (calculated)
	Short	User barefoot
	125 pF	User wearing rubber-soled shoes
	90 pF	User wearing chest waders
	54 pF	User wearing rubber-soled shoes, standing on 1 in. foam sheet

4.1 WE 188A Response Versus User Test Procedure

Tests were conducted to characterize the response variability of the WE-188A test set under a variety of user-controlled measurement conditions, as discussed in Section 3.3. The results of these tests are plotted as frequency response curves in Figure 19. The parameter being measured by the vertical axis in the figure is the test set detection threshold in volts; that is, the voltage at which the test set first indicates a potential hazard by a flashing red LED. All seven curves were obtained using pedestal configuration 1 and a metal pedestal.

The variability of test set response as a function of user technique is clearly evident in Figure 19. The least sensitive test set response for these tests is given by curve A. For this situation, the test set is hand-held (hand grip area controlled by foil) and the user is wearing lightweight rubber-soled shoes while standing on a 1-in. thickness of plastic foam insulation. This is a "typical" or average worst-case probe response. A less sensitive response would likely result if the user were of smaller stature and with a smaller hand grip area, or if the user were wearing gloves.

An increase in sensitivity over curve A of approximately 20% at 60 Hz can be obtained simply by adding the conductive cap and W1BU cord to the test set handle, even without hand contact with the cap, as shown by curve B.

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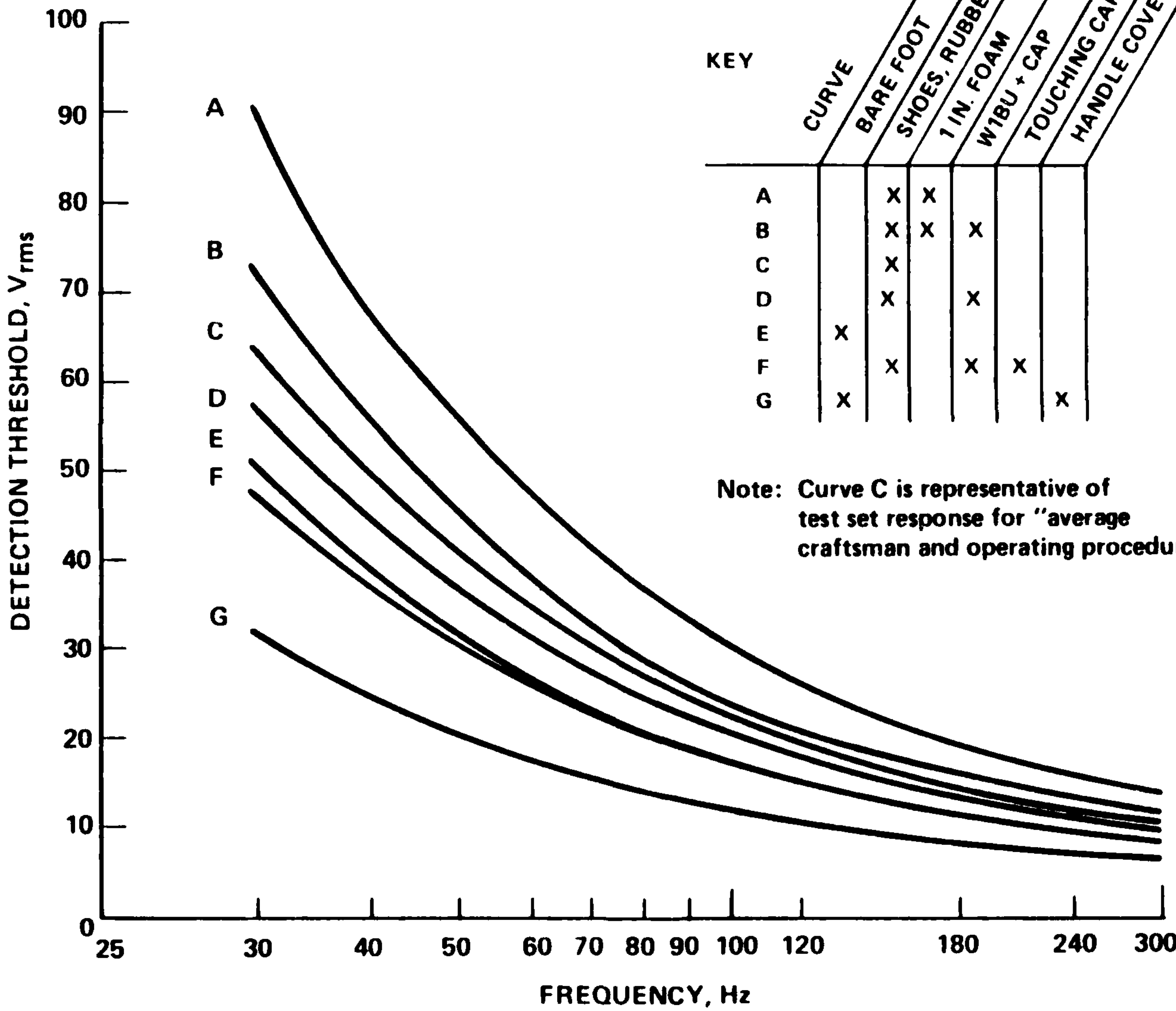


KEY

CURVE	BARE FOOT	SHOES, RUBBER SOLE	1 IN. FOAM	W1BU + CAP	TOUCHING CAP	HANDLE COVERED
A		X	X			
B		X	X	X		
C		X				
D		X		X		
E	X					
F		X		X	X	
G	X					X

Note: Curve C is representative of test set response for "average craftsman and operating procedures"

FIGURE 19. WE 188A TEST SET RESPONSE VERSUS USER TEST PROCEDURE.

Additional gains in sensitivity over both curves A and B can be obtained by repeating the tests after first removing the layer of foam insulation used to simulate ground cover (see curves C and D).

It should be noted for purposes of comparison that curve C is representative of test set response for a 150-lb craftsman wearing rubber-soled shoes, standing on bare earth, and employing normal test set operating procedures (i.e., not using the W1BU cord and conductive cap). Hereafter in this report these user conditions will be referred to as "average craftsman and operating procedures."

The practical upper limit of test set sensitivity for a given hand grip area is illustrated by the nearly identical responses of curves E and F. In curve E the user is barefoot and standing directly on the ground mat, thereby effectively bypassing his body-to-ground capacitance. Test set response is then controlled only by the hand grip area. For curve F the user is wearing shoes and standing on the ground mat. He is employing the W1BU cord and conductive cap, with his hand touching the cap to at least partially bypass his body-to-ground capacitance. While under actual field conditions a user would rarely, if ever, be barefoot, it is certainly plausible for a user to be standing on soil without ground cover and using the W1BU cord and cap.

Curve G represents the theoretical upper limit of sensitivity of the WE-188A test set for all conditions and is presented as a reference. For this test the handle of the test set was completely covered with foil to provide the maximum attainable hand grip area. The user was also standing barefoot on the ground mat, eliminating any body-to-ground capacitance effects. To obtain this level of sensitivity under field conditions the user would need to grip the test set with both hands so as to completely cover the handle, while at the same time either standing barefoot on bare ground or using the W1BU cord and cap and touching the bare metal of the cord's test clip (bypassing the cap impedance).

Table 2 presents a tabulation of the data used to generate the curves of Figure 19. The data above the dashed line indicate frequency/test condition combinations for which the test set's threshold voltage exceeds its 60 Hz specification of 50 V_{rms}.

TABLE 2. WE 188A THRESHOLD VOLTAGE, V_{rms}, VS. USER TEST PROCEDURE

Frequency, Hz	Test Condition						
	A	B	C	D	E	F	G
30	91.0	73	64	58	50	47	32
40	69.0	57	49	45	39	37	25
44	64.0	--	--	41	--	35	--
50	57.0	47	42	37	32	30	21
60	48.0	38	36	32	27	26	17.8
70	42.0	33	31	28	24	23	15.6
76	39.0	--	--	26	--	22	--
80	37.0	29	27	25	22	21	14.1
90	--	--	24	--	--	18.9	--
100	31.0	25	23	21	17.8	17.4	12.0
120	27.0	22	20	17.9	15.5	15.2	10.5
180	19.3	15.6	15.0	13.3	11.6	11.4	8.2
240	15.8	13.5	12.0	11.0	9.7	9.6	7.1
300	13.7	11.8	10.7	9.7	8.6	8.5	6.5

Condition Key:

A = Rubber-soled shoes on 1-in. foam

B = Rubber-soled shoes on 1-in. foam, using W1BU cord and cap, not touching cap

C = Rubber-soled shoes directly on ground mat ("average craftsman and operating procedures" as defined in section 4.1)

D = Rubber-soled shoes directly on ground mat, using W1BU cord and cap, not touching cap

E = Barefoot, directly on ground mat

F = Rubber-soled shoes directly on ground mat, using W1BU cord and cap, touching cap

G = Barefoot, directly on ground mat, maximum hand grip area.

4.2 WE 188A Response Versus Telephone Plant Configuration

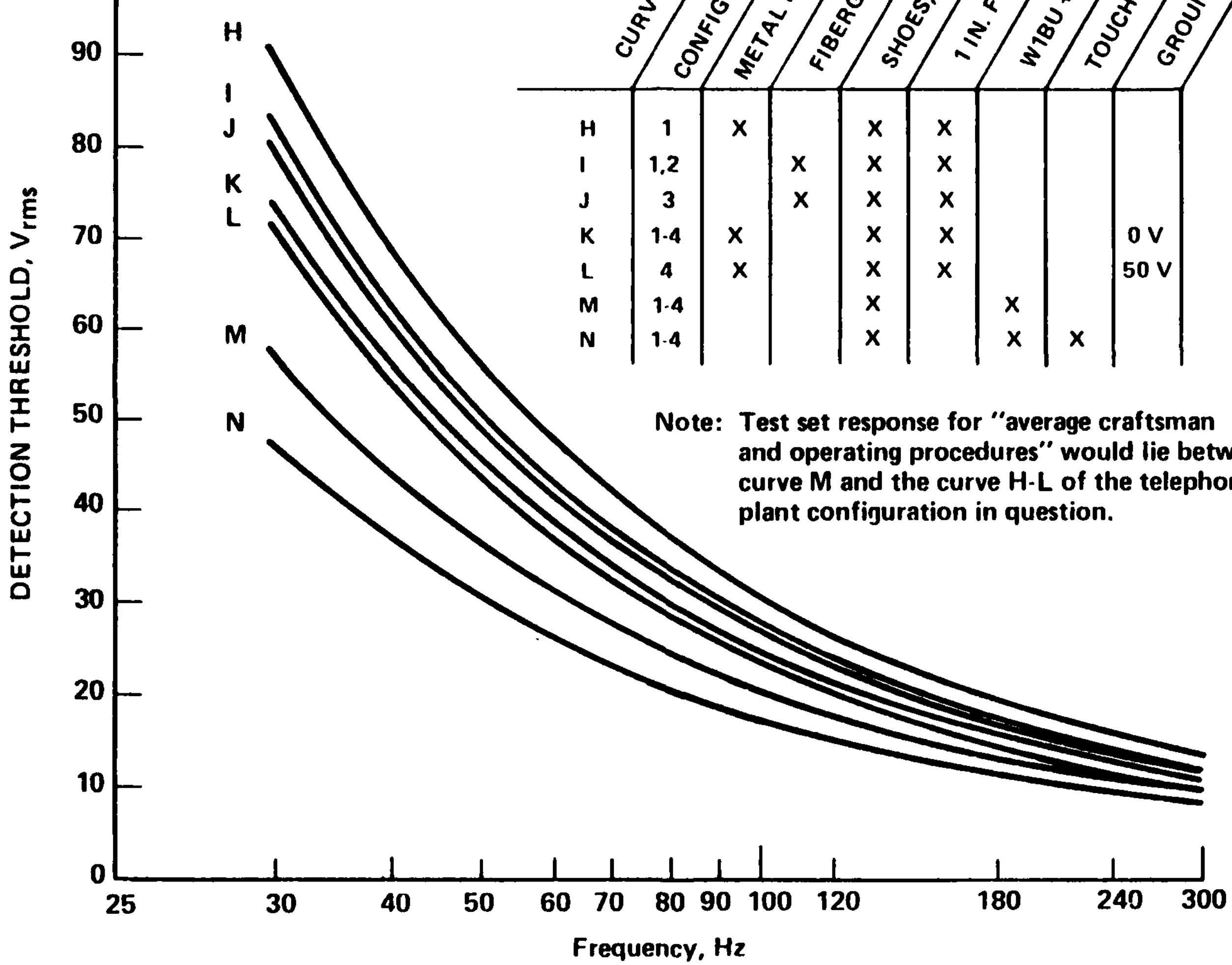
The following tests were performed to investigate whether the response of the WE 188A test set was sensitive to differences in telephone plant configuration. First, user test procedures were standardized to control for possible variations caused by user technique. Then, based on the response characteristics of Figure 19, typical worst-, intermediate-, and best-case probe sensitivity test conditions were adapted as follows:

- **Worst-Case (Least Sensitive):** test performed by user wearing rubber-soled shoes and standing on a 1-in.-thick layer of plastic foam insulation; hand grip area limited to area of copper foil
- **Intermediate-Case (More Sensitive):** test performed by user wearing rubber-soled shoes and standing directly on the ground mat; conductive cap and W1BU cord used, hand grip area limited to area of copper foil and does not contact conductive cap.
- **Best-Case (Very Sensitive):** test performed as in Intermediate, but with hand grip area expanded so that hand is in contact with the conductive cap.

Each of these three test conditions was applied to the laboratory mock-ups of the five telephone plant configurations described in Section 3. The response curves for ground-level configurations 1 through 4 are presented in Figure 20. Numerical data are presented in Table 3.

These test conditions relate to likely craftsman operating situations as follows: a 150-lb craftsman wearing rubber-soled shoes, standing on bare earth, and employing normal test set operating procedures (not using W1BU cord and conductive cap) would produce a test set sensitivity somewhere between the worst- and intermediate-case responses for the particular telephone plant configuration. The same craftsman standing on thick underbrush, crushed stone, or a concrete pad would produce a worst-case test set sensitivity. If, however, the craftsman employs the test set in conjunction with the W1BU cord and conductive cap (as would be standard operating procedure in areas of high electrostatic coupling such as under a transmission line), the test set response would be representative of the intermediate- to best-case sensitivity test conditions.

The worst-case, or least sensitive, test conditions are represented by curves H through L. The WE 188A test set was found to be least sensitive when



KEY

CURVE	CONFIGURATION	METAL PED	FIBERGLASS PED	SHOES, RUBBER SOLE	1 IN. FOAM	W1BU + CAP	TOUCHING CAP	GROUND RING VOLTAGE
H	1	X		X	X			
I	1,2		X	X	X			
J	3		X	X	X			
K	1-4	X		X	X			0 V
L	4	X		X	X			50 V
M	1-4			X		X		
N	1-4			X		X	X	

Note: Test set response for "average craftsman and operating procedures" would lie between curve M and the curve H-L of the telephone plant configuration in question.

FIGURE 20. WE 188A TEST SET RESPONSE -- GROUND LEVEL EQUIPMENT.

TABLE 3. WE 188A THRESHOLD VOLTAGE, V_{rms}, VS. GROUND LEVEL PLANT CONFIGURATION

Frequency, Hz	Test Condition/Configuration						
	Worst-Case Sensitivity					Intermediate	Best-Case
	H	I	J	K	L	M	N
30	91	83	80	74	72	55-58	47
40	69	63	61	56	55	42-45	37
44	64	58	56	52	50	39-41	35
50	57	52	50	46	44	35-37	30
60	48	44	42	40	38	30-32	26
70	42	38	37	34	33	26-28	23
76	39	36	35	32	30	24-26	22
80	37	34	33	31	29	23-25	21
100	31	28	27	25	24	18.7-20.9	17.4
120	27	24	23	22	20	16.5-17.9	15.2
180	19.3	17.7	17.1	15.9	14.3	11.9-13.3	11.4
240	15.8	14.5	14.0	13.0	11.3	9.7-11.0	9.6
300	13.7	12.5	12.1	11.3	9.6	8.6-9.7	8.5

Configuration Key:

H = Configuration 1, metal pedestal, open pedestal ground

I = Configurations 1 and 2, fiberglass pedestal, bad shield ground or bond

J = Configuration 3, fiberglass pedestal, bad shield ground or bond

K = Configurations 1-4, metal pedestal, bad shield ground or bond

L = Configuration 4, metal pedestal, ground ring at 50 V, bad shield ground or bond

M = All configurations, metal or fiberglass pedestals

N = All configurations, metal or fiberglass pedestals.

Note: Test set threshold voltage for "average craftsman and operating procedures" would lie between the intermediate-case M and the worst-case H-L corresponding to plant configuration.

testing a metal pedestal in configuration 1 with a simulated bad pedestal ground (curve H). The test set response was similar and about 10% more sensitive when testing cable shields for all fiberglass pedestal configurations, as shown by curves I and J. The test set was most sensitive under worst-case test conditions when testing cable shields for a metal pedestal where a ground ring was present (curves K and L). As shown in the figure, the probe was slightly more sensitive when the ground ring was elevated in potential with respect to remote ground. Curve K also represents the response that would be produced by a configuration 1 metal pedestal with a bad shield/pedestal bond or by a configuration 2 or 3 metal pedestal with a bad shield ground.

The WE 188A test set responded in an essentially identical manner to all ground-level pedestal configurations when intermediate-case test conditions were employed, as illustrated by curve M. A similar but slightly more sensitive response was observed for best-case test conditions (curve N). Thus, use of the conductive cap and W1BU cord are shown to be effective in reducing the variability of the test set's response to different telephone plant configurations.

Figure 21 presents curves of the WE 188A test set response for configuration 5, that of an aerial telephone cable or pole-mounted equipment. The worst-case test conditions do not apply here, because the test set is designed to use the W1BU cord and conductive cap as a ground reference in these situations. Curves O through R present the test set response for the intermediate- and best-case test conditions. The ground mat used as reference for the test set's W1BU cord was either grounded to the building's electrical system or left floating, as indicated in the key to this figure. As the curves indicate, the response, or sensitivity, of the test set had a variance of only about 10% at 60 Hz for all test conditions in this configuration. This can be explained by the fact that the capacitance-to-ground of a user several feet above the ground is very small, and the relatively constant impedance-to-ground of the conductive cap and W1BU cord dominate the test set response. It should also be noted that the overall sensitivity of the WE 188A test set in this configuration is considerably less than when the cord and cap are used to test ground-level equipment. In fact, the test set's best-case response for configuration 5 is in the same range as its worst-case response

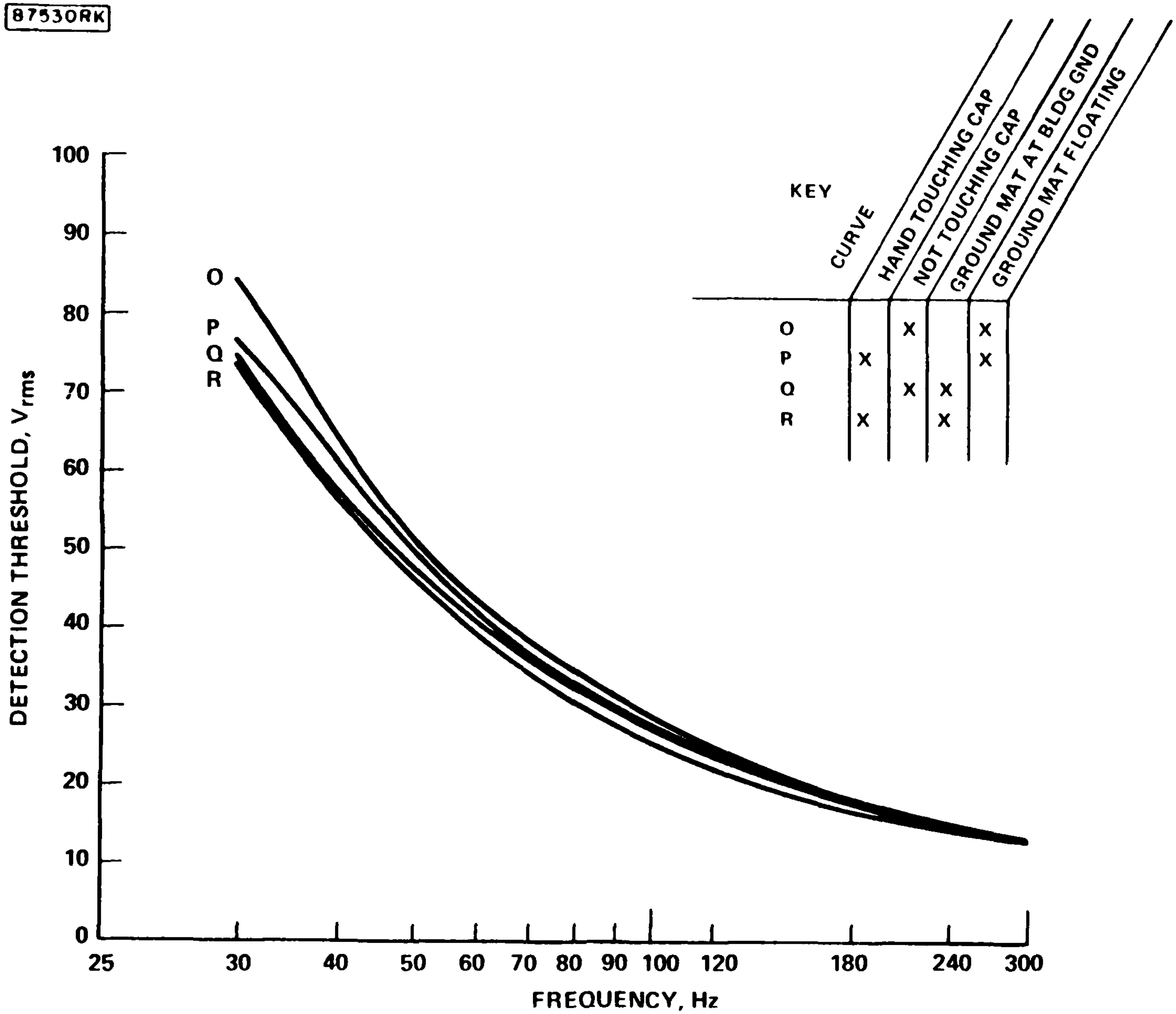


FIGURE 21. WE 188A TEST SET RESPONSE -- AERIAL EQUIPMENT.

for configurations 1 through 4. The measurement data used to generate Figure 21 are presented in Table 4.

TABLE 4. WE 188A THRESHOLD VOLTAGES, V_{rms}, ON AERIAL PLANT

Frequency, Hz	Test Condition			
	0	P	Q	R
30	85	77	75	74
40	66	62	58	57
50	52	51	48	47
60	45	43	42	39
70	40	37	36	35
80	35	33	35	31
100	29	28	28	26
120	25	24	25	22
180	18.3	17.2	18.1	16.4
240	15.0	14.0	14.7	13.7
300	13.0	12.1	12.9	11.9

Condition Code:

0 = Hand not touching cap, ground mat floating

P = Hand touching cap, ground mat floating

Q = Hand not touching cap, ground mat at building ground

R = Hand touching cap, ground mat at building ground.

4.3 WE 188A Response to Modulated ELF Voltages

The response of the WE 188A test set was also characterized for test voltages consisting of the modulated signals produced by an ELF communications system (MSK signals), and for MSK signals in combination with 60 Hz voltages. These measurements were conducted for telephone plant configurations 1 through 4 under intermediate- and worst-case test conditions. The resulting data are shown in Table 5.

TABLE 5. WE 188A THRESHOLD VOLTAGES, V_{rms}, FOR MIXED SIGNAL CONDITIONS

Test Signal Frequency Composition	Worst-Case Sensitivity* Pedestal Configuration 1	2	3	4	Intermediate-Case Sensitivity** Pedestal Configuration 1	2	3	4
44 Hz CW	64	58	56	50	41	41	40	39
44 Hz MSK	58	54	51	46	38	37	36	35
44 Hz MSK 75%/25% 60 Hz CW	55	52	49	45	37	36	35	34
44 Hz MSK 50%/50% 60 Hz CW	51	48	46	40	34	32	33	32
44 Hz MSK 25%/75% 60 Hz CW	47	44	43	38	33	31	31	29
60 Hz CW	48	44	44	39	32	31	32	30
76 Hz MSK 25%/75% 60 Hz CW	45	43	40	36	31	29	29	28
76 Hz MSK 50%/50% 60 Hz CW	42	39	36	32	29	28	27	26
76 Hz MSK 75%/25% 60 Hz CW	37	35	34	29	26	26	24	23
76 Hz MSK	36	34	33	29	25	25	24	22
76 Hz CW	39	36	35	30	26	25	25	24

*User with rubber-soled shoes standing on 1 in. foam

**User with rubber-soled shoes standing on ground mat using conductive cap and W1BU cord, hand not touching cap.

Note: Test set threshold voltage for "average craftsman and operating procedures" would lie between the worst-case and intermediate-case threshold for each pedestal configuration.

Examination of the Table 5 data yields some interesting observations. First, the test set is consistently about 10% more sensitive to an MSK modulated signal of a particular frequency than to an unmodulated or continuous wave (CW) signal at the same frequency. This can be explained by the fact that an MSK signal contains frequency components higher than its center frequency, and that the sensitivity of the test set increases with frequency. The test set thus responds to the higher frequency components of the MSK signal. A second observation, which follows basically from the first, is that test set sensitivity increases as the percentage of 60 Hz signal added to the MSK signal increases for MSK signals centered below 60 Hz. Similarly, test set sensitivity also increases as increasing percentages of an MSK signal centered above 60 Hz are added to a 60 Hz signal. A third observation is that trends in the response of the WE 188A test set to modulated ELF signals with

respect to telephone plant configuration and test methodology are the same as the trends observed for unmodulated and single frequency signals as described in the previous sections.

5. DISCUSSION AND CONCLUSIONS

A WE 188A test set was tested under laboratory conditions to determine its response to frequency, user methodology, telephone plant configuration, and modulated ELF signals. The test set depends on capacitive coupling to the user and from the user to ground as a link in its test circuit. Its voltage detection threshold is therefore highly nonlinear and inversely proportional to frequency.

User methodology has been shown by experiment to be capable of causing up to a threefold change in the test set's detection threshold at 60 Hz, from 18 to 48 V. This range is caused by changes in the test set's capacitive coupling to ground as determined by the type and thickness of ground cover to the test point, the user's foot size and type of footwear, the user's body size (height and weight), the area of the test set handle covered by the user's hand (related to hand size), and the use of gloves. User-induced variances can be reduced significantly by using the test set's conductive cap and W1BU cord as an auxiliary ground reference; this can increase the sensitivity of the test set by 20% to 30% at 60 Hz.

The WE 188A test set exhibits some variation in response (about 20% at 60 Hz) with respect to different ground-level plant configurations when used without the conductive cap and W1BU cord and when some ground cover is present (least-sensitive test conditions). In this situation, the test set is least sensitive to voltage on an ungrounded metal pedestal, and most sensitive to voltage on a shield in a grounded metal pedestal. The increase in sensitivity in the latter situation is very likely due to increased capacitive coupling to ground because of the proximity of the user's body to the grounded upright metal equipment case. The test set was not adversely affected by the presence of a ground ring installed to mitigate touch voltages on larger metal equipment cases. The only change in response was a slight increase in test set sensitivity when the ground ring and equipment case were driven at 50 V with respect to remote ground. The response of the test set was stable and

showed little variation when the test set was used on simulations of aerial telephone plant and used in conjunction with the conductive cap and W1BU cord to provide a ground reference. Some variations in test set sensitivity would be expected in the field, however, because of differences in hand grip area among users.

Tests conducted using modulated voltages of the type an ELF communications system would induce on telephone plant indicate that the WE 188A test set is consistently about 5% more sensitive to MSK modulated voltages than to unmodulated voltages at the same frequency. Using 60 Hz response as a reference, test set sensitivity is decreased about 25% for a modulated signal at 44 Hz, and increased about 20% for a 76 Hz modulated signal. Otherwise, all previously noted response trends for single frequencies are valid for modulated ELF voltages as well. The test set also responds as expected to combinations of modulated ELF and 60 Hz voltages.

In conclusion, the WE 188A test set was found to satisfactorily detect voltages in excess of 50 V_{rms} with a modulated ELF frequency of 76 Hz, as well as with all combinations at 60 Hz CW and modulated 76 Hz, in all of the laboratory tests and conditions described earlier. The test set's frequency response dictates that it will always be more sensitive at 76 Hz, the ELF Communications System's principal operating frequency, than at 60 Hz.

However, the high degree of response variability with respect to user methodology inherent in the test set's design does not preclude plausible test conditions for which the test set might not detect voltages in excess of 50 V at 60 Hz or even 76 Hz. Examples of two such conditions are a user of small stature with a correspondingly smaller hand grip area, or a user wearing gloves in winter. Either of these conditions could significantly reduce test set sensitivity. Test set response under these scenarios was not quantified.

Laboratory tests showed that the test set was able to detect modulated 44 Hz voltages (or 44 Hz/60 Hz combinations) of 50 V under conditions applying to "average craftsman and operating procedures" as defined in Section 4.1. However, test set sensitivity at 44 Hz will be decreased by ground cover scenarios such as thick underbrush, crushed stone, or concrete pads. This should not be of immediate concern as 44 Hz operation is not contemplated for ELF Communications System operation. The test set's limitations at 44 Hz can

probably be overcome by changes in standard user procedures, such as mandatory use of the W1BU cord and conductive cap. Further testing would be necessary to develop and verify such procedures.

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1. "188A Test Set (Stop Lite) Description and Use." Bell System Practices, AT&T Co. Standard, Sec. 081-705-102, Issue 3, October 1983.

2. "Transmission and Outside Plant Design Procedures, T1 Digital Line, Carrier Engineering." Bell System Practices, AT&T Co. Standard, Sec. 855-351-101, Issue 7, February 1982.

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